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Sensitivity of Energy Use to Factors in Pipe Replacement Planning for a Large Water Distribution System

M. Prosser[a], V. Speight[b], Y. Filion[c]*

[a]Sameng Inc., 1500 Baker Center, 10025 – 106 Street, Edmonton, Alberta, Canada
[b]Latis Associates, 1001 19th Street N, Suite 1200, Arlington, Virginia, USA
[c]Dept. of Civil Engineering., Queen's University, Kingston, Ontario, Canada

Abstract

A previous study completed by the authors used a life-cycle energy analysis approach to evaluate energy associated with pipe replacement schedules in a large distribution system, thereby identifying several factors that contributed to life cycle energy consumption. This paper examines the impact of parameters within the calculation of life cycle energy consumption with a sensitivity analysis. Leak duration, leak volume, break rate model coefficients, and pump efficiency were evaluated. The results of the analysis suggest that investments in improving pump efficiency are likely to yield greater energy savings than investments in leak detection or leakage volume quantification.

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Keywords: Water distribution systems; water main replacement; energy use; pipe breaks; leakage; sensitivity analysis

1. Introduction

Energy use in water distribution systems is influenced by system design, demand, pump efficiency, and water loss from breaks, among other factors. To make design and rehabilitation decisions that reduce energy use, it is necessary to understand the importance of these factors. The aim of this paper is to present a sensitivity analysis to rigorously examine the impact of a number of significant system factors on energy use and pipe replacement scheduling as applied to a large, complex water distribution system. Previous work by Filion et al. [1] developed a novel life-cycle

* Corresponding author. Tel.: +1 (613) 533-2126; fax: +1 (613) 533-2128.
E-mail address: yves.filion@queensu.ca

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energy analysis (LCEA) that incorporated an economic input-output model of the United States economy. The study quantified energy use in the fabrication stage of water mains (embodied energy), the use and operation stage (but did not include pumping as the New York Tunnels primary supply system is supplied by gravity), and the disposal stage of water mains. A sensitivity analysis on the components of the LCEA found that the embodied energy was sensitive to changes in pipe fabrication energy use and pipe replacement length, which stemmed from a parameter termed breakage growth rate. This finding emphasized the dominance of the embodied energy of new pipe in the absence of any pumping in the New York Tunnels primary water supply system. The typical break length and initial break rate were found to have a small influence in the 20-year replacement scenario investigated and the solution was insensitive to the energy of disposal for the pipes, the energy of recycling, the recycling rate and the turbine efficiency.

Ghimire and Barkdoll [2] performed sensitivity analyses on factors affecting energy use in water networks. They examined 7 distribution networks to determine the impact of increasing and decreasing water demand and tank storage and varying the location of pumping stations on energy use. The authors found that system demand had a significant impact on energy use in all 7 systems, with lower demands resulting in lower pipe velocities and friction energy losses. The sensitivity analysis described in this paper builds on a LCEA completed in a study by Prosser et al. [3] which examined the energy use tied to three practical pipe replacement scenarios for a large water distribution system with complex pumping operations.

1.1. Case Study Utility

This work examines the impact of system factors on energy use in a large-scale water distribution network in the Midwestern United States. The water distribution network serves approximately 1 million customers with an average daily demand of 530 mega litres per day (MLD). The network characteristics are summarized in Table 1. The water main stock in the network is represented by over 140,000 individual segments in a pipe inventory database including information on pipe materials, diameter, age, and historical pipe break data. The pipe information was used to group the pipe stock into classes by pipe material, diameter, and age. The majority of pipes fall into the 5-50 year-old age range but there is a significant length of pipe that exceeds 75 years of age.

Table 1. Summary of case study system (adapted from [4])

System Component	Quantity
Water Treatment Plants	3
Pumping Stations	28
Storage Tanks	37
Base Average Demand excluding Leakage	470 MLD
Estimated Leakage	60 MLD
Total Average System Demand	530 MLD
Total Length of Pipe	5,900 km
Base Average Annual Pumping Energy	55.9 million kWh

The LCEA study of Prosser et al. [3] developed three practical pipe replacement plans and examined the energy use implications for each plan. Replacement Plans A and B are based on the break performance of each pipe class in the network. In Plan A, pipes are replaced once a low break rate threshold of 25 breaks per 100 kilometers is exceeded. In Plan B, pipes are replaced once they reach a high break rate threshold of 50 breaks per 100 kilometers of pipe. For both Plans A and B, pipes are replaced at the age of 100 years if they have not exceeded the break rate threshold before that time. In Plan C, pipes are replaced when they reach 75 years of age regardless of performance. Pipes older than 75 years at the start of the planning horizon (2013-2020) are replaced in the first decade.

The pipe replacement Plans A through C are indicated in Fig. 1. In Plans A and B, a large quantity of deteriorated pipe that currently exceeds the break rate thresholds is replaced in the first decade (1,637 km in Plan A and 1,285 km in Plan B). Following the opening decade, pipe replacement decreases significantly until the 2070 decade where a large quantity of pipe has deteriorated to exceed the break rate and age thresholds (1,023 km in Plan A and 1,028 km in Plan B). In Plan C, pipes older than 75 years are replaced in the opening 2020 decade and the rate of replacement is reasonably uniform over the remainder of the planning period. The annual embodied and operational energy replacement Plans A through C was compared to a baseline scenario with no replacement. The results indicated that an annual operational energy savings between 8.9 and 9.6 million kWh by 2070 was achievable through pipe replacement, but would require annual embodied energy expenditures of 5.6 – 112 million kWh to replace ductile iron pipes with diameters ranging from 150 – 400 mm [3].

2. Methodology

The LCEA study by Prosser et al. [3] considered a number of life-cycle activities in the fabrication and operation stages of pipe replacement. The activities included in the fabrication stage were: (i) pipe and liner production, (ii) backfill, bedding and asphalt production, (iii) excavation and backfill/bedding compaction, and (iv) the transport of pipe and liner to the site and the disposal of native soil. The activities included in the operation stage were: (i) pumping, additional leakage caused by pipe breaks, frictional loss in pipes, and the embodied energy in treatment chemicals in water lost to leakage.

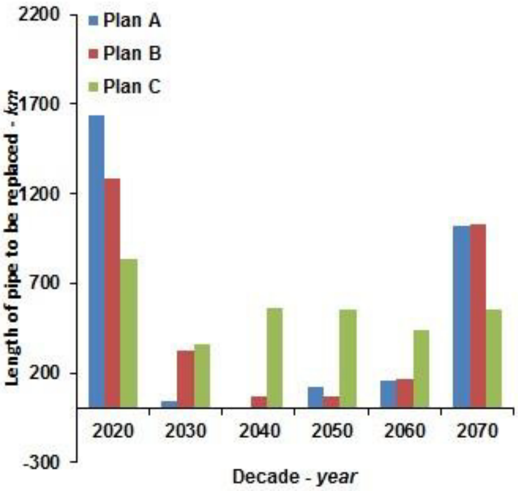

Fig. 1. Summary of pipe replacement Plans A, B and C [3]

Pipe maintenance and cleaning and the end-of-life stage were not considered. The sensitivity analysis in this study examines two important components of operational energy loss linked to leakage: (i) the energy required to pump water through an increasingly leaky system to meet demands and manage friction and; (ii) the embodied energy of the lost water. The pumping energy was estimated using a hydraulic model for a range of leakage volumes and the embodied energy was estimated to be 47.3 kilowatt-hours per megalitre (kWh/ML) using data from a study with similar source water and treatment requirements [5].

The change in pumping energy use associated with increases in leakage was calculated for the baseline "no-replacement" scenario and replacement Plans A through C across a 50-year time horizon to provide a relationship between flow and leakage volume (Fig. 2). This figure indicates that a 1 MLD increase in leakage results in an increase of 0.058 million kWh per year in pumping energy use in the "no-replacement" scenario. For Plans A, B and C, a 1 MLD increase in leakage resulted in an increase of 0.047, 0.065, and 0.077 million kWh/yr in pumping energy, respectively. The difference in slope for each replacement plan reflects the variability in location of the replaced pipes within the overall system configuration. As different classes of pipes are replaced, certain areas within the distribution system undergo a reduction in energy loss due to friction, while other areas do not. A system-wide reduction of pumping energy cannot be expected for any pipe replacement scenario that targets only certain pipe classes. By using these energy-flow factors in the sensitivity analysis to estimate operational energy, information about the site-specific nature of each replacement plan was preserved. The total operational energy use was taken to be the sum of the pumping energy and the embodied energy in the leaked water.

2.1. Selection of Parameters for Sensitivity Analysis

While the embodied energy of pipe fabrication activities is important and has a high level of uncertainty, it was not considered in this sensitivity analysis. For a chosen pipe material, the embodied energy for water main construction is determined by the mining and manufacturing processes that occur outside of the decision-making of a water utility. Therefore this analysis focuses only on factors related to operational energy. Fig. 2 shows the allocation of total operational energy across different categories of energy usage, as determined for Plan A and averaged across the entire planning period [4]. 70 percent of the energy is delivered to customers as pressure at the connection. Water demand was judged to have a low level of uncertainty given that it was well characterized with household water consumption data and was intentionally held fixed to explore the relationship between leakage, pump efficiency parameters and energy use in this study. Therefore, the volume of water delivered to customers was not considered further in the sensitivity analysis.

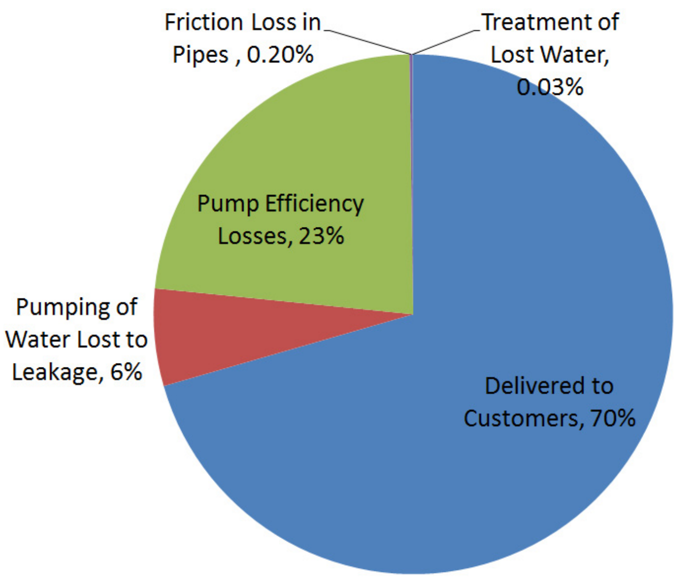

Fig. 2. Components of total operational energy for replacement Plan A

Of the remaining 30 percent, the majority (23%) of operational energy is associated with pump efficiency losses (Fig. 2). The energy required to pump the water lost to leakage represents 6 percent of the total energy for replacement Plan A, which is an aggressive replacement plan and therefore has a relatively low leakage rate. The energy loss from friction and treatment of the leakage water were both negligible in this case. Therefore the leakage volume and pump efficiency were selected as the focus of this sensitivity analysis. Leakage was examined by varying the parameters of leak duration, leakage volume per break, and pipe break rate, while pump efficiency was examined directly by varying the efficiency of pumps in the system.

2.2. Sensitivity Analysis Factors

2.2.1 Leak Duration

Depending on the type of leak and the utility's ability to respond, the time between the identification of a leak and its repair can vary greatly. Industry guidance suggests leak identification-to-repair durations that range from 1 day for a major distribution main break to 46 days for a water service connection break [6]. Prosser et al. [3] assumed a leakage duration of 3 days for major cracks and holes and one year for all other minor breaks. For the present sensitivity analysis, the leak identification-to-repair duration was varied from 1 to 7 days for major cracks and holes, while the minor breaks remained undetected.

2.2.2 Leak Volume

In Prosser et al. [3], the leakage volume was calculated by multiplying the flow rate for the specific break type by the corresponding leak duration (see Section 2.2.1). An average operating pressure of 70 psi and hole diameter of one inch were assumed and converted to a flow based on tables provided in industry guidance [6]. In the present sensitivity analysis, the flow rates for each break type are varied from 0.5 to 2 times the original values while holding the leak durations constant.

2.2.3 Break Rate Model Coefficients

Historical break rate records were used to calibrate time-linear break forecasting models to predict the number of breaks between 2020 and 2070 (the planning horizon) for each pipe class [4]. The time-linear break forecasting model was chosen because of its simplicity, because high-order models did not show an improvement in fit of the break data, and because the break data was not sufficiently detailed to warrant the use of a more complex model. The general form of the time-linear model used is as follows:

$$N_{brk} = A + Bt \tag{1}$$

where N_{brk} = number of breaks per year; A and B are time-linear coefficients; and t = time. In the sensitivity analysis, the time-linear model parameters A and B were varied by ± 30%, in increments of 10%, to reflect the uncertainty in the time-linear model predictions.

2.2.4 Pump Efficiency

High-lift pumps used in water distribution systems typically have efficiencies averaging 70%, ranging widely depending on the condition of the pump, the operating conditions of the network, and the maintenance performed [7]. Field-test data for pump efficiency was not available from the case study utility. In this sensitivity analysis, pump efficiency was varied from 60% to 80% to reflect a ±10% deviation in the typical pump efficiency of 70%.

3. Results

Fig. 3 provides a summary of the sensitivity analysis results, with the average impact on annual operational energy (in percent) plotted for each of the four tested parameters across the baseline and pipe replacement plans. It was found that pump efficiency had the largest impact on the operational energy. Increasing the pump efficiency by 33%, from 60% to 80% efficiency, resulted in a 33% decrease in operational energy across all scenarios due to the linear relationship between brake horsepower and pump efficiency.

Variations of ± 30% in the break rate model coefficient had a minimal impact (less than 1%) on operational energy for all replacement plans, with a slightly higher impact (5.7%) in the no-replacement scenario. For leakage volume, energy use was found to be moderately sensitive in the baseline no-replacement scenario, with an average change of 14.3% resulting from varying the leakage volume by a factor of 0.5 to 2.0. However, for the replacement plans where leakage is kept to a minimal amount, the results in Fig. 3 show that energy use is weakly sensitive to a change in leakage volume. Further, Fig. 3 shows that varying the leak duration for major leaks from 1 to 7 days did not significantly change (less than 1%) the energy use in the system under any of the replacement scenarios.

4. Discussion and Conclusions

In this sensitivity analysis, it was found that the leakage volume and the leak duration play a lesser role in the operational energy use of a large water utility as long as pipe replacement is undertaken to control leakage within reasonable levels. The baseline no-replacement plan allows leakage to increase from 11% to 18% of average daily demand between 2020 and 2070. By contrast, the replacement plans manage leakage to within 5% of average daily demand throughout the planning horizon. In this context, doubling the leakage volume per leak had only a small impact on the annual operational energy (less than 3%). For systems with a higher baseline leakage rate, similar to that of the no-replacement scenario, the impact of leakage volume can be more significant. This indicates the potential for interventions that reduce leakage volume, such as pressure management schemes, do have a noticeable impact on the operational energy for systems with higher leakage levels. However, the relative insensitivity of the operational energy to leak duration across all replacement scenarios indicates that rapid response (1 day versus 1 week) is less important than other interventions in terms of energy savings.

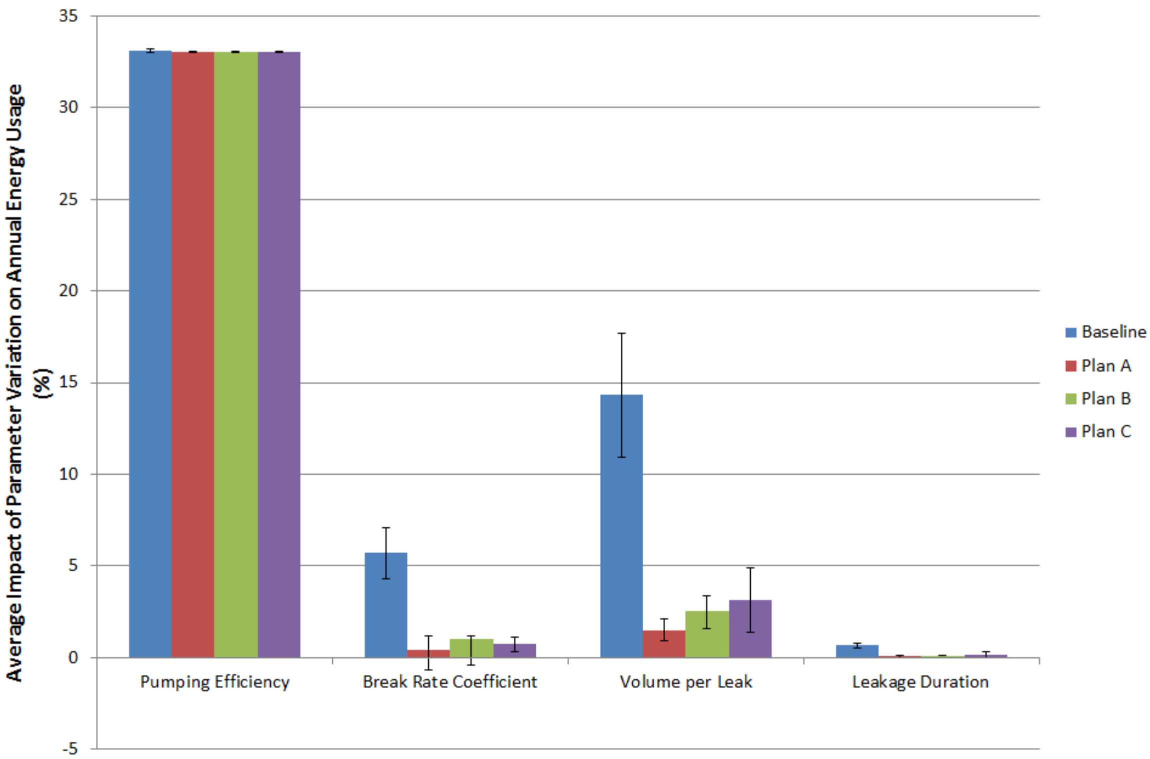

Fig. 3. Impact of parameters on annual operational energy use (error bars indicate maximum and minimum value across all decades analyzed)

Many utilities invest significant effort in developing customized pipe break rate models. This sensitivity analysis with a simplified time-linear break rate model showed that the prediction of break rates had a small impact on the operational energy for the no-replacement scenario, and negligible impact for any of the replacement plans.

A clear result is the impact of pump efficiency on operational energy. An increase in pump efficiency from 60% to 80% can have significant effect in operational energy, particularly in the context of large distribution systems with many pumps. An investment in pump testing and efficiency improvement could have a significant payback through reduced energy consumption. For a system like the case study network with an average pumping energy usage of 55.9 million kWh per year, a 10% reduction in energy consumption through pump efficiency improvement could equate to a significant cost and environmental impact saving.

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